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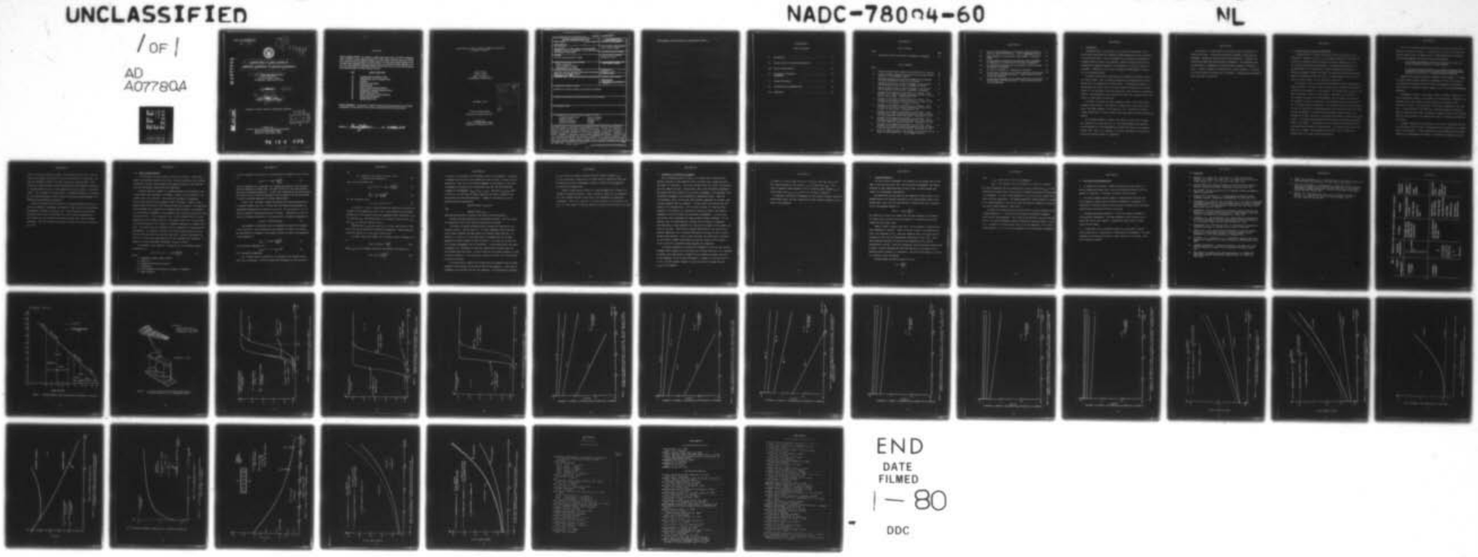

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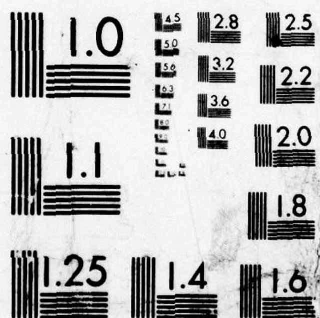

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(6) SIGNIFICANCE OF LARGE SCATTER OF COMPOSITE PROPERTIES TO AIRCRAFT RELIABILITY.

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SIGNIFICANCE OF LARGE SCATTER OF COMPOSITE PROPERTIES
TO AIRCRAFT RELIABILITY

Pei Chi Chou
Robert Croman

DREXEL UNIVERSITY
Philadelphia, Pennsylvania

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Design criteria	Scatter factor
Composite materials	Strength
Aircraft structure	Fatigue

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Statistical calculations have been made for the static load reliability of an aircraft fleet assuming typical metalic and composite strength distributions. A factor of safety is defined as the element strength divided by the "weakest of the fleet" strength. Element strength is typical "A" or "B" basis material allowables. "Weakest of the fleet" strength is calculated statistically assuming each aircraft to be made up of a realistic arrangement (in-series or in-parallel) of critical elements. Similar calculations are also made for fatigue life. It is shown that the reliability of the current damage tolerant design, such as multiple load path and crack
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20. stoppers, can be specified in quantitative terms.

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I. Introduction

The general goal of this project is to study the implications of the large scatter associated with composite strength properties to the reliability of aircraft structures. Certain components of an aircraft are considered as arranged either in series, or in parallel. Based on realistic distribution parameters for composite material, the reliability of a fleet of aircraft is calculated. Emphasis is put on static strength but implications to fatigue life are discussed briefly.

For metal structures, the main concern on reliability is fatigue failure, not static failure. This is because reliability is the problem only when the failure life, or strength, has a large scatter. If the material behaves in a deterministic way, where values of failure stress and fatigue life are finite numbers for all specimens in the same population, there would be no reliability problem. The deterministic way of specifying limit load, allowable stress, and factor of safety would be sufficient.

For metal, the scatter in static strength is small, with Weibull shape parameter larger than 20. The scatter in fatigue life, on the other hand, is large, with shape parameter in the range of 2 to 5. Therefore, for metal, fatigue reliability is of most concern; static load poses no serious reliability problem.

For composite materials, however, the scatter for both static strength and fatigue life is large (see Fig. 1). The shape parameter for composite static strength is in the neighborhood of 10, and less than two for composite fatigue life. Thus, it is necessary to study the reliability of both static failure and fatigue failure for composites.

In Section II, a brief review of the current status of structural reliability is given. A few points particularly relevant to this study are mentioned. Section III gives the static load reliability. Parametric calculations are made with series-parallel arrangements. The parameters used are the number of components in an aircraft and the number of aircraft in a fleet. A factor of safety is defined and its values calculated. In Section IV, a brief account of fatigue case is presented. Conclusions and recommendations are given in Section VI.

II. Current Status of Structural Reliability

A detailed review of current structural criteria as specified by the Department of Defense, as well as a few proposed approaches to the structural criteria for composite material airframes is given by Manning, et al. [1]. The current USAF structural requirement, as contained in MIL-STD-1530, [2], and MIL-A-8860, [3], is explained in a paper by Haviland and Tiffany [4]. Recently, Weinberger, Somoroff and Riley [5] presented the criteria for Naval production composite aircraft structures. We shall mention here a few of the points in these criteria that are relevant to this study.

The current criteria are basically deterministic, and are originally for metal structures. For static loads, the limit load is defined as the maximum operational load expected to be encountered. The ultimate load is equal to the limit load times a factor of safety, which is generally not less than 1.5. Two allowable stresses are used (MIL-HDBK-5) [6], for primary structures the "A" allowable is used, (at least 99% of the population must have values above the A-allowable with 95% confidence). For secondary structure, the B-allowable is used, (at least 90% of the population must have values above the B-allowable with 95% confidence). The material yield allowable stresses shall not be exceeded at the limit load level; the material must sustain ultimate load without failure. The fatigue load spectrum should be based on the planned operational usage of the vehicle. The fatigue life of the structure must exceed one service life-time multiplied by a scatter factor. The scatter factor used by the USAF is 4, or larger, under average load spectrum. The U.S. Navy uses a scatter factor of 2 under extreme load spectrum.

The current criteria recognize that aircraft structure has small flaws, defects, and cracks at delivery. To ensure that the structure will last the required service life, two damage tolerant design approaches are available, the fail-safe approach, and the slow-crack growth approach.

- In the fail-safe approach, unstable crack growth is locally contained by multiple load paths, or crack stoppers.

- In the slow-crack growth approach, the cracks are prevented from attaining the critical size for unstable rapid propagation during the life of the structure, or between inspection intervals.

Among the few proposed structural criteria, we shall mention the concept of "time-to-first failure" proposed by Freudenthal [7] [8], and the concept of treating the reliability at three levels: the components, the structure, and the fleet, as proposed by Rogers, et al. [9] (the so-called NASA Monograph Rationale).

Freudenthal's concept is that among a fleet of identical aircraft, the first catastrophic failure of one aircraft is of most concern. Therefore, the expected time to first failure is used instead of the current practice mean time to failure. The reliability of the fleet is dependent on the fleet size. If each aircraft in the fleet has a fixed and identical reliability, then the larger the fleet size, the smaller the expected time to first failure, which can be calculated by the weakest-link theory, or extreme-value distribution theory.

In Roger's approach, the reliability of the fleet is calculated from that of the aircraft, which in turn is calculated from the reliability of the components of the aircraft. (It also stipulates that the component can be further divided into subcomponents and elements. The method of calculation from one level to the next is always the same). The reliability of the fleet is calculated by the weakest-link theory; if one of the aircraft in a fleet fails, the fleet is considered "failed." We shall call this an in-series model. They treated the relation between aircraft reliability and the component reliability in the same manner, that is, if one component fails, the aircraft is considered failed. This is again an in-series model. No redundant component is considered. Nor are fail-safe measures, such as multiple load path and crack stoppers, considered in the reliability calculation.

We may also mention that the concept of treating reliability by levels of aircraft, component, subcomponent and element is used by the Navy and mentioned by Weinberger, Somoroff, and Riley in [5]. Other pertinent work on aircraft reliability may be found in Refs. [10]-[13]. In [13], Lemon and Manning give a brief overview of the structural reliability problem, and a list of selected references. This list includes all relevant articles on structural reliability up to 1974.

III. Static Load Reliability

For this study, we shall consider a fleet of n aircraft. We are interested in the weakest aircraft in the fleet. We shall calculate, with a certain reliability (say 95%), the strength of the weakest aircraft; or the load that will fail the weakest aircraft with 95% probability.

We shall study the strength of a primary structure of the aircraft, such as wing torque box, stabilizer, or fuselage. Failure of this structure is considered fatal to the aircraft. This structure consists of m components. For the wing torque box, the components could be the spars. Figure 2 shows a typical wing box structure of the advanced Harrier and its spars. For simplicity, we shall assume the m components are arranged either in-series, or in-parallel. For the in-series arrangement, if one component fails, the whole structure and thus, the aircraft fail. In the in-parallel case, if one component fails, the other components can still support the load. The parallel arrangement is essentially the multiple-load path, crack stopper, or redundancy approaches in "damage tolerance." In actual cases, the components are in a combination of series-parallel arrangements. For instance, the spars of the Harrier wing torque box can sustain the limit load after one auxiliary spar fails. We shall also assume the load is of a fixed value (deterministic) and the components are independent. A summary of the series-parallel arrangement is given in Table I.

The strength of the component is assumed to be of two-parameter Weibull distribution, or

$$F_{\Sigma}(\sigma) = P(\Sigma \leq \sigma) = 1 - \exp[-\left(\frac{\sigma}{\sigma_{\beta}}\right)^{\alpha}] \tag{1}$$

where

Σ = component strength random variable

σ = value of Σ

F = cumulative distribution function

P = probability

σ_{β} = scale parameter (characteristic strength of component)

α = shape parameter

If the m components are in-series, the distribution of strength of the structure is

$$F_{\Sigma m}(\sigma) = 1 - \exp[-m\left(\frac{\sigma}{\sigma_\beta}\right)^\alpha] \qquad (2)$$

If the m components are in-parallel, the strength distribution of the structure cannot be expressed in simple form. For small values of m, the exact distribution can be calculated numerically. In Ref. [14], equations for the distributions for values of m up to seven are presented; they are based on the uniform sharing of load by surviving components (no stress-concentration).

In Ref. [15], the bundle strength distribution has also been expressed in a recursion formula, (Eq. 9.2). We have used this formula and calculated the in-parallel distribution for values of m up to 20. For the case of m = 50, we used the simplified large bundle equation of Daniel. Symbolically, we may express the strength distribution of a structure with m in-parallel components as

$$F_{\Sigma m'}(\sigma) = \text{function}(\alpha, \sigma_\beta, m) \qquad (3)$$

The strength of the aircraft will be considered the same as the strength of this structure. We are interested in the weakest in a fleet of n aircraft. The distribution of strength of this weakest aircraft in terms of the parameters of the component is

$$F_{\Sigma mn} = 1 - \exp[-mn\left(\frac{\sigma}{\sigma_\beta}\right)^\alpha] \qquad (4)$$

for m in-series components, and

$$F_{\Sigma m'n} = 1 - [1 - F_{\Sigma m'}(\sigma)]^n \qquad (5)$$

for m in-parallel components.

For a certain value of reliability, the strength of the weakest-of-the-fleet can be calculated. We shall consider 95% reliability in this derivation.

Let

$$\sigma_{wf} = \text{strength of the weakest aircraft in the fleet with 95\% reliability,} \tag{6}$$

then, for the in-series case,

$$F_{\Sigma mn} = 0.05 = 1 - \exp[-\,mn\left(\frac{\sigma_{wf}}{\sigma_\beta}\right)^\alpha] \tag{7}$$

or

$$\frac{\sigma_{wf}}{\sigma_\beta} = [\frac{1}{mn}\,\ell n\left(\frac{1}{0.95}\right)]^{1/\alpha} \tag{8}$$

For the in-parallel case,

$$[1 - F_{\Sigma m'}\,(\sigma_{wf})]^n = 0.95 \tag{9}$$

In figures 3, 4, and 5 we have plotted the cumulative distribution of strength of the component F_Σ, with $\alpha = 10$. Also plotted are the strength distribution of the aircraft with seven components either in-parallel, $F_{\Sigma m'}$, or in-series, $F_{\Sigma m}$. The distributions of the weakest of 100 aircraft, $F_{\Sigma mn}$ and $F_{\Sigma m'n}$, are shown in Figures 4 and 5.

Calculations of σ_{wf}/σ_β are made for $\alpha = 2,5,10$, and 20 and $m = 7,20$, and 50 for both in-series and in-parallel arrangements. These results are plotted in Figures 6 to 11 as σ_{wf}/σ_β versus curves.

In order to gain more insight, let us define a Factor of Safety (F.S.) as

$$\text{Factor of Safety} = \frac{\sigma_{0.95}}{\sigma_{wf}} \tag{10}$$

where $\sigma_{0.95}$ is the strength that 95% of the component will exceed, or

$$0.95 = \exp[-\left(\frac{\sigma_{0.95}}{\sigma_\beta}\right)^\alpha\ ] \,. \tag{11}$$

It may also be considered as the allowable stress of the component. In general, a designer will use this as the strength, and will not apply a stress that will exceed this. Now, due to the series arrangement of the aircraft in the fleet, the weakest of the fleet has a strength much less than the 95% reliability strength of the component, $\sigma_{0.95}$, or $\sigma_{wf} < \sigma_{0.95}$. The ratio $\sigma_{0.95}/\sigma_{wf}$, which we call F.S., is the factor of safety required, such that no failure of the fleet would occur with 95% reliability. Looking at it another way, if the applied stress is restricted to

$$\text{applied stress} \leq \sigma_{0.95}/\text{F.S.}$$

then

$$\text{applied stress} \leq \sigma_{wf} .$$

This would assure that no failure of the fleet with 95% reliability.

We have used 95% reliability for illustration purposes. For other values of reliability, such as 99%, similar calculations can be made.

The factor of safety as defined above is plotted as a function of n in Figures 12 and 13. We have used m = 7, or seven components in the structure, which closely simulates the eight spars in the Harrier wing torque box. In Figure 12, a value of $\alpha = 20$ is used, which is representative of the shape parameter of static strength of metal structures. Two curves are plotted, one for in-series arrangement, one for in-parallel. As mentioned before, the actual arrangement is a combination of these two, represented by points within the area between these two curves. It can be seen that the present practice of using a factor of safety of 1.5 is sufficient to ensure no failure for a few thousand aircraft in the fleet.

The dotted line in Figure 12 is plotted with the assumption that the shape parameter of the aircraft is the same as that of the component. It may also be considered as an aircraft with only one component. The characteristic strength,

σ_{β}, is used in the formula, instead of the 95% reliable strength $\sigma_{0.95}$. It can be seen that a larger factor of safety would be required in this case. We labled this curve by Freudenthal, because it follows the basic approach he used for the fatigue case.

Figure 13 shows similar curves for a shape parameter of 10, typical for strength of composite materials. Here, a factor of safety of 1.5 is adequate for a few thousand aircraft in the fleet if the components are essentially in-parallel. Thus, it is seen that it is more important to have multiple load path, or crack stopper in composite material structures than in metal structures.

IV. Advantage of In-Parallel Arrangement

From an engineering point of view, it is obvious that a structure with multiple load path is more desirable than a structure with a single load path. The former is "fail-safe"; after one load path fails, the rest of the structure can still support the load. Statistically, this is the in-parallel arrangement. The single load path structure is an in-series arrangement. The advantage of the in-parallel arrangement can be expressed in quantitative terms. There are two advantages, first, the structure with parallel components has a higher value of shape parameter than the component. In other words, the structure has less scatter in its strength value. This is shown in Figure 14, where the shape parameter of the aircraft (or structure) is plotted in terms of the number of components, for both in-series and in-parallel arrangements. It can be seen that for the series arrangement the shape parameter remains unchanged. For the parallel case, the shape parameter increases with the number of components. This high value of shape parameter will increase the strength of the weakest aircraft in the fleet. Note that the strength distribution of the aircraft with parallel components is not a Weibull distribution, and does not have a clearly defined shape parameter. Here, we have calculated the coefficient of variation of the aircraft strength distribution and used the formula curve in Figure 1 to get a value of an equivalent shape parameter for comparison.

The second advantage of the parallel arrangement is that the high reliable strength (95% or higher) of the structure may be larger than that of its component. In general, the characteristic strength of the structure is smaller than that of its component, as can be seen from Figure 3. However, for certain values of α and m, the 95% reliable strength of the structure may be higher than the $\sigma_{0.95}$ of the component.

In Figure 15, it can be seen that for $\alpha = 10$ and $m = 100$, the value of the 95% reliable strength of the aircraft, σ_{ac}, is larger than $\sigma_{0.95}$. For a value of component shape parameter α of 2, the 95% reliable strength σ_{ac} is always larger than $\sigma_{0.95}$ ($= \sigma_{ac}$ for $m = 1$), as shown in Figure 16.

To summarize, the parallel arrangement has less scatter (steeper cumulative distribution curve), and has a larger 95% (or 99%) reliable strength, as compared to the component.

V. Fatigue Reliability

For the in-series arrangement, the formulas for the fatigue case are the same as those for the static case. For the parallel arrangement, the fatigue situation is more complicated than the static case. We shall present here results of a preliminary investigation.

We assume that the S-N_β curve of the component is known, where S is the maximum stress of the fatigue load and N_β is the characteristic value of the fatigue life. Also, the life distribution at a given stress level is assumed to be a two-parameter Weibull, or

$$F(N) = 1 - \exp[-\left(\frac{N}{N_\beta}\right)^\alpha].$$

For simplicity, we shall also assume that the shape parameter is the same at all stress levels, and only the scale parameter, or characteristic life N_β, changes with the stress level.

Figure 17 shows a typical S-N_β curve. Let us consider a structure with seven components in parallel. Under the initial stress S, the characteristic life of the components is N_β. After one component fails, the stress level is increased to 7S/6, and the corresponding characteristic life is N_β^1. After three component failures, the stress in the remaining is 7S/4, and the characteristic life N_β^3. With this information, and the recursion formula given by Daniel, we have calculated the life distribution of the aircraft with m component either in-series, or in-parallel. The life of the weakest in a fleet of n aircraft is also calculated.

We shall define the Scatter Factor (S.F.) as

$$S.F. = \frac{N_{0.95}}{N_{wf}}$$

where

$N_{0.95}$ = 95% reliable life of the component

N_{wf} = 95% reliable life of the weakest in a fleet of n aircraft

Note that Freudenthal used the characteristic life N_β, instead of $N_{0.95}$, as his definition of scatter factor, and he did not consider the aircraft as consisting of m components. He used a shape parameter of 4 for the aircraft fatigue life, which is overly conservative. The shape parameter for metal specimens is around 4; the shape parameter of the aircraft with more than one component in parallel must have a shape parameter of more than 4.

In Figure 18, we have plotted the scatter factor for seven components with a shape parameter of 4. In this case, the series and parallel arrangement curves are not distinguishable. For a fleet of 100 aircraft, from our analysis an S.F. of 5 would be adequate, whereas Freudenthal's approach requires a value of 7. In Figure 19, we have plotted the S.F. for 20 components. For a fleet of 100 aircraft, a S.F. of 4 is just adequate for the in-parallel arrangement.

VI. Conclusions and Recommendations

1. In comparison with metals, composite materials have more scatter in static strength and fatigue life. Thus, more extensive statistical study is needed for reliability of composite structures, than for metals.

2. The current damage tolerance design in using multiple load paths and crack stoppers is statistically in-parallel arrangement of components. The reliability of aircraft structures with this type of design can be calculated quantitatively, and should be done in the future.

3. Freudenthal was overly pessimistic. He did not realize the benefit of the in-parallel arrangement. The shape parameter of the structure can be larger than that of the component. Unnecessarily high values of scatter factor are not needed.

4. A large panel can be considered as made up of many small "coupons." These coupons are in a combination of series-parallel arrangements. The shape parameter of the panel most likely is larger than that of the coupon. This effect should be studied.

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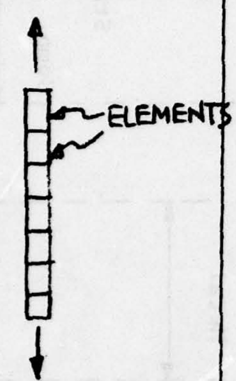
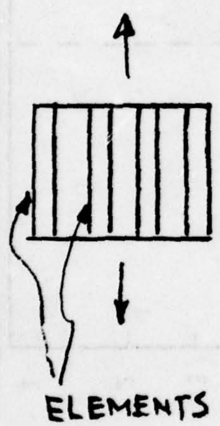
Table I. Statistical Series and Parallel Arrangements of Elements

Features / Arrangements	Graphical representation	Principle	Examples	Theory and equations
n-elements in-series		the whole unit is considered failed when one of its elements fails.	• elements physically in-series • brittle material • aircraft in a fleet	weakest link theory; simple equation.
n-elements in-parallel		surviving elements can still sustain the load.	• elements physically in-parallel • multiple-load path • redundant structure • crackstopper • softening strip • test coupon to large structures	static-bundle theory fatigue - theory to be developed.

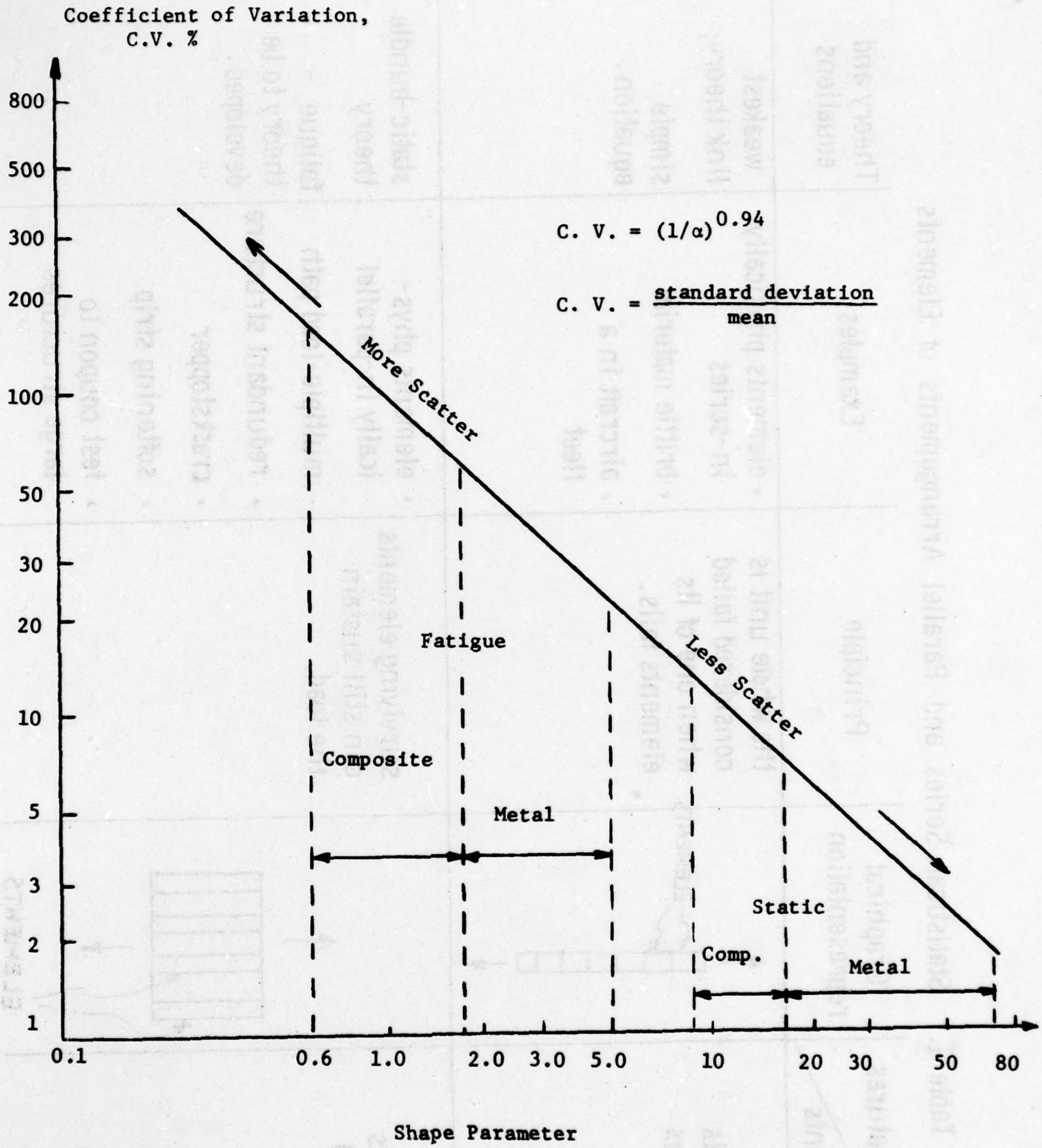


Figure 1. Relation Between Shape Parameter and Coefficient of Variation

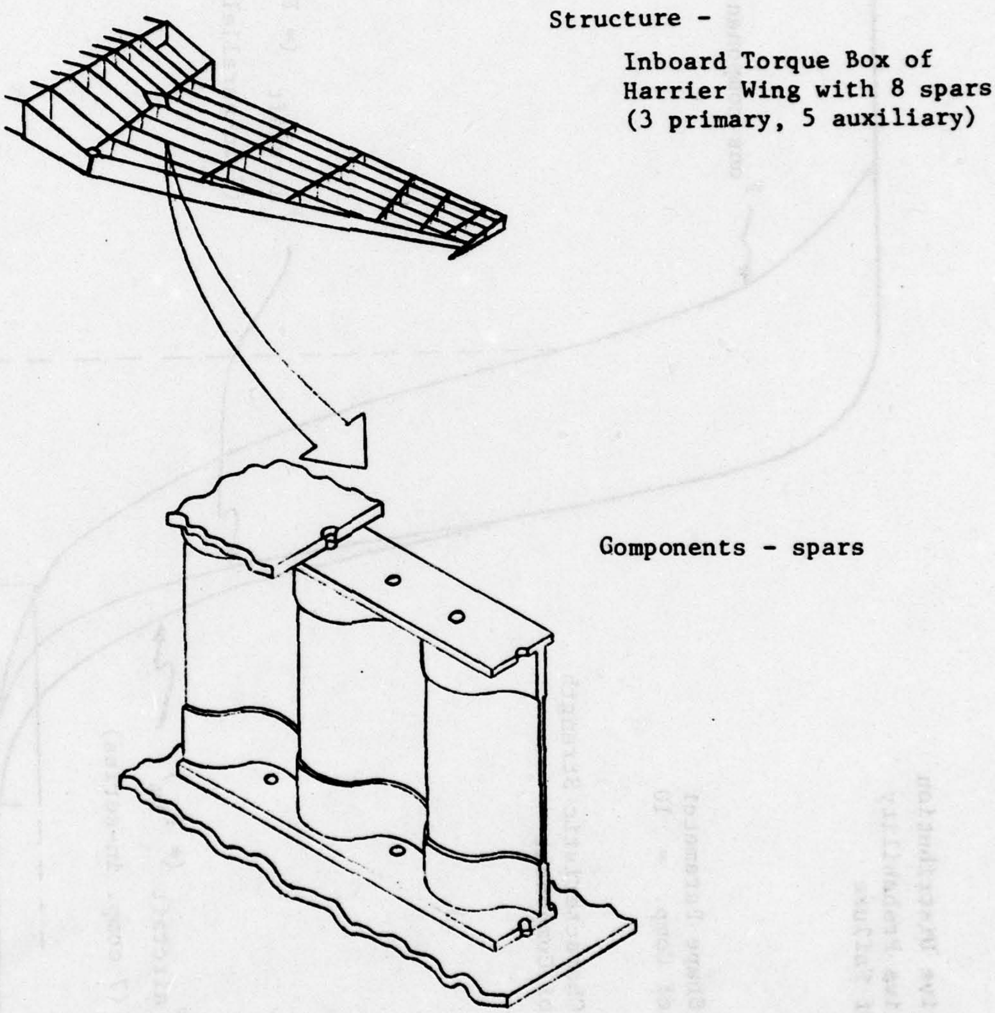


Figure 2. A Typical Primary Structure (Wing Torque Box) of the Advanced Harrier, and its Components (spars).

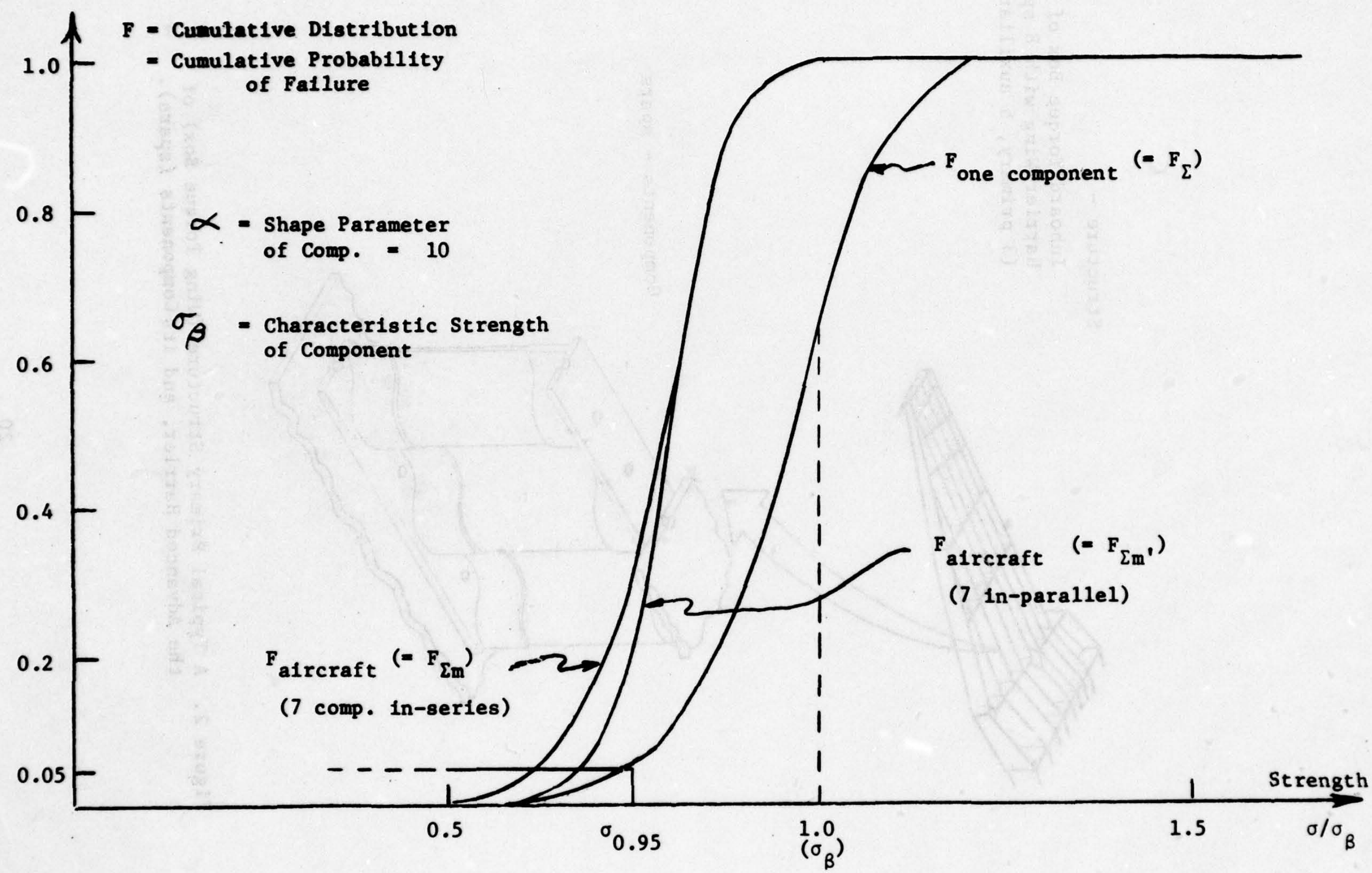


Figure 3. Cumulative Distribution of Static Strength of one Component and Seven Components In-Series and In-Parallel

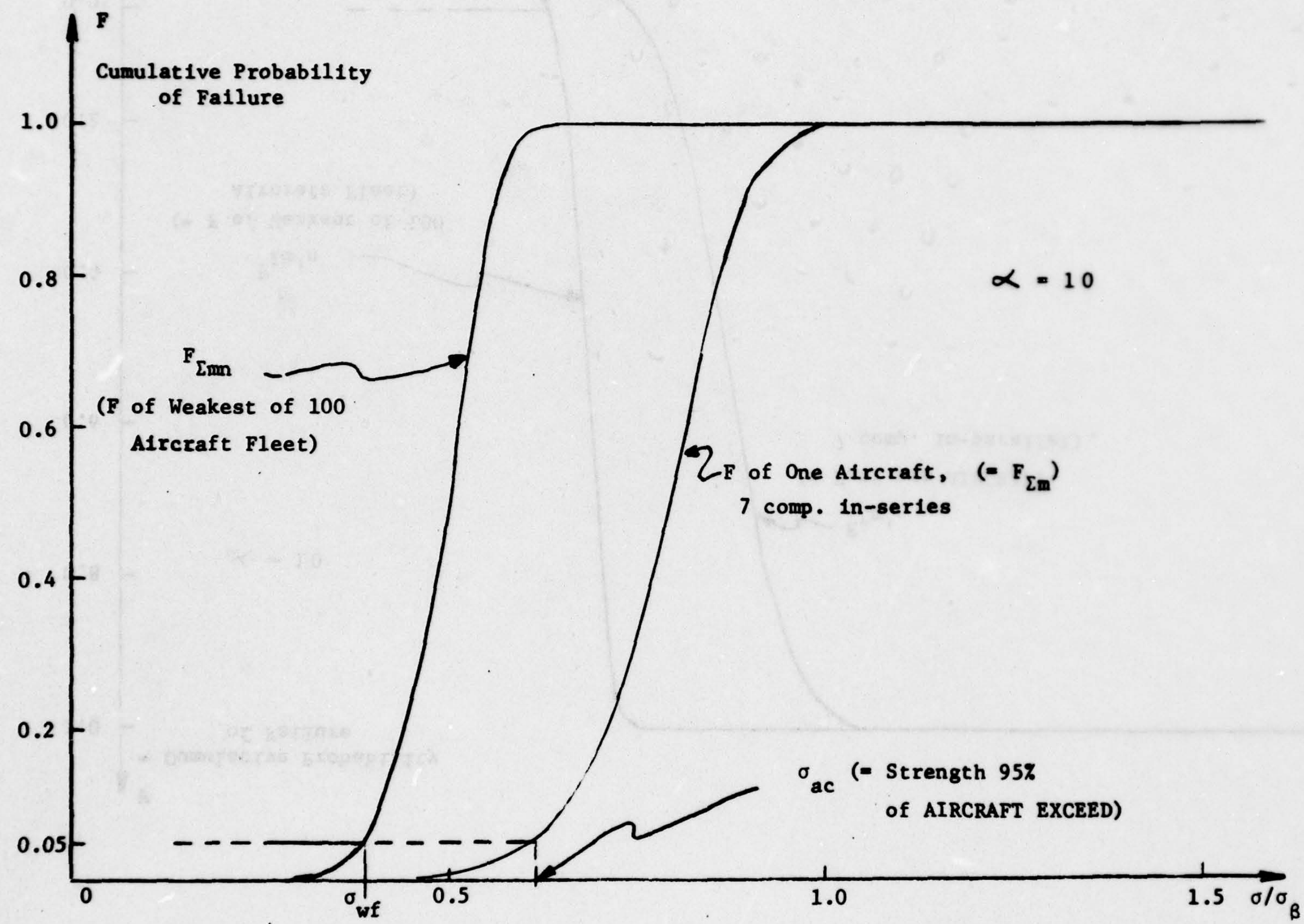


Figure 4. Cumulative Distribution of Static Strength of One Aircraft and the Weakest of 100 Aircraft. Components in Series

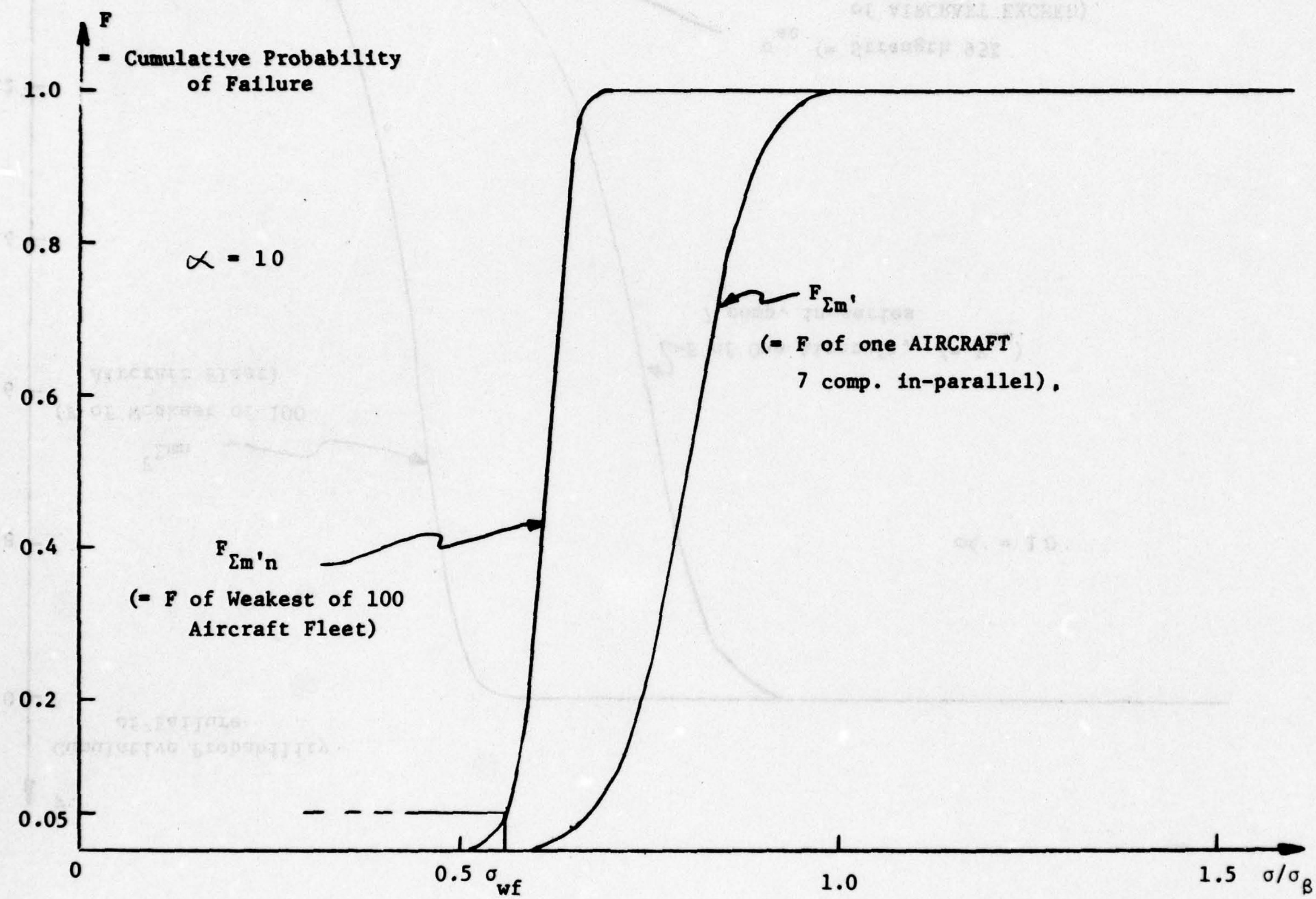


Figure 5. Cumulative Distribution of Static Strength of One Aircraft and the Weakest of 100 Aircraft. Components in Parallel

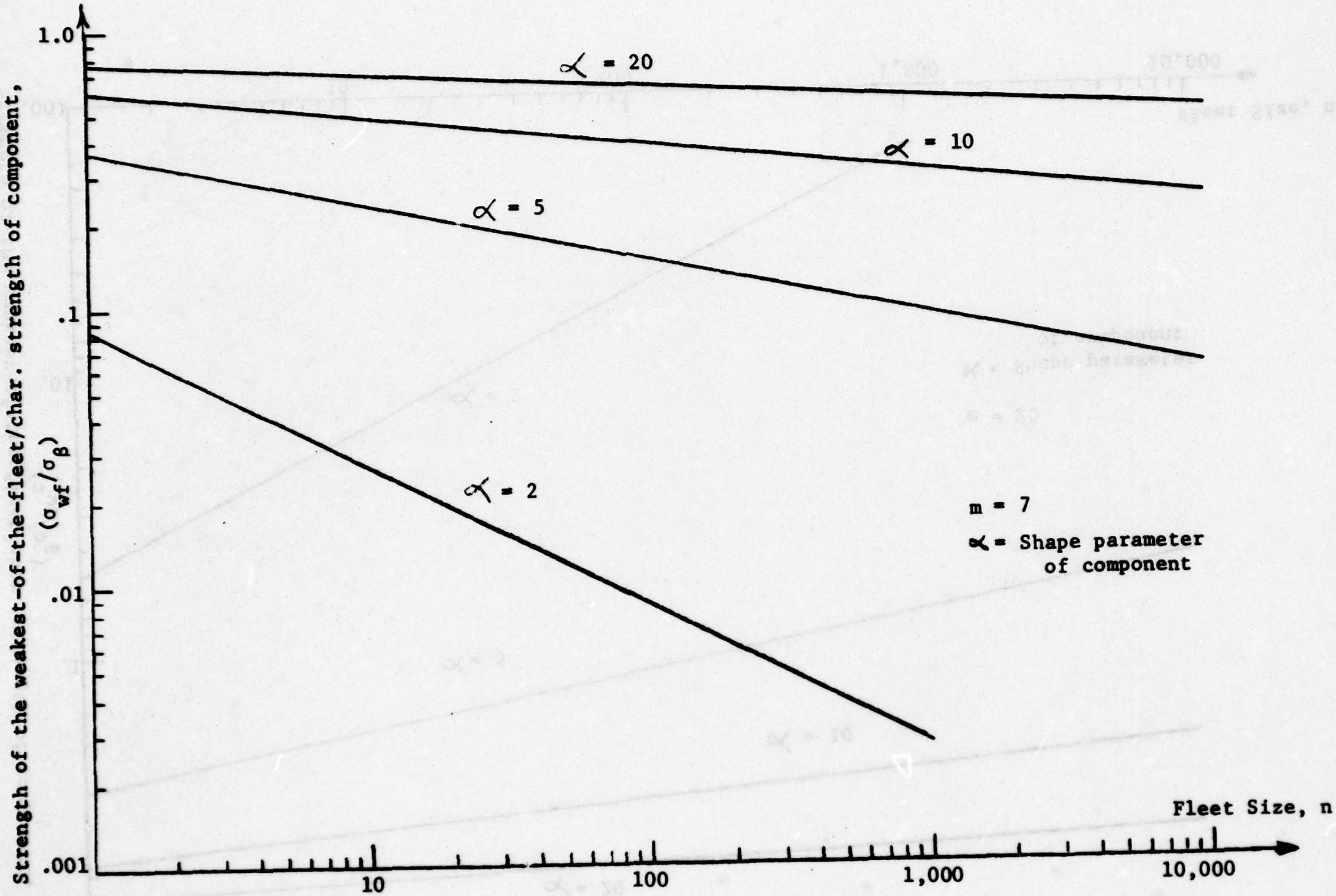


Figure 6. Strength of the Weakest-of-the-Fleet, of n Aircraft. Each Aircraft with 7 Basic in-series Components; Failure of any is Fatal to the Aircraft. Reliability of 95%

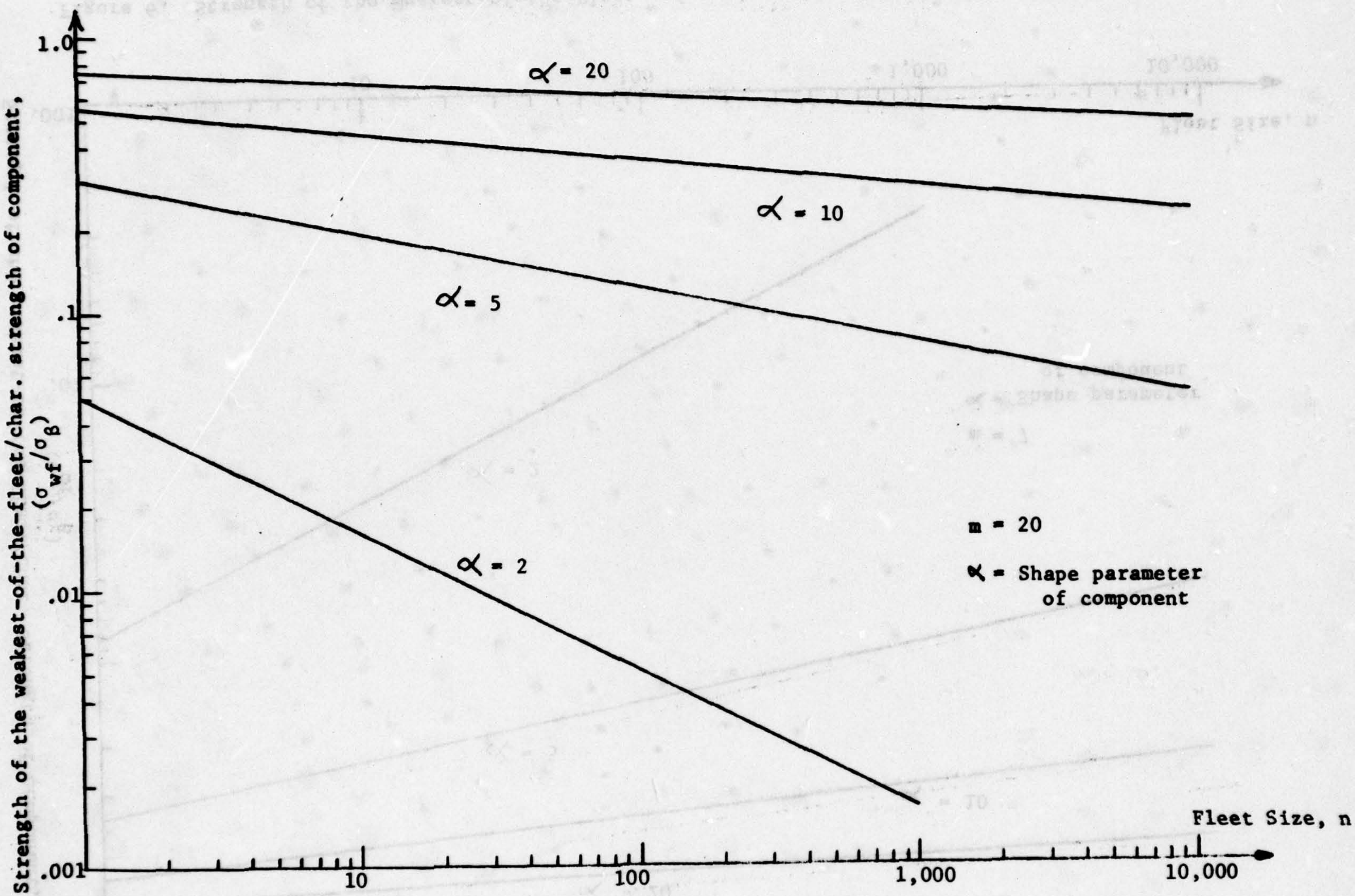


Figure 7. Strength of the Weakest-of-the-Fleet, of n Aircraft. Each Aircraft with 20 Basic in-series Components. Failure of any is Fatal to the Aircraft. Reliability of 95%.

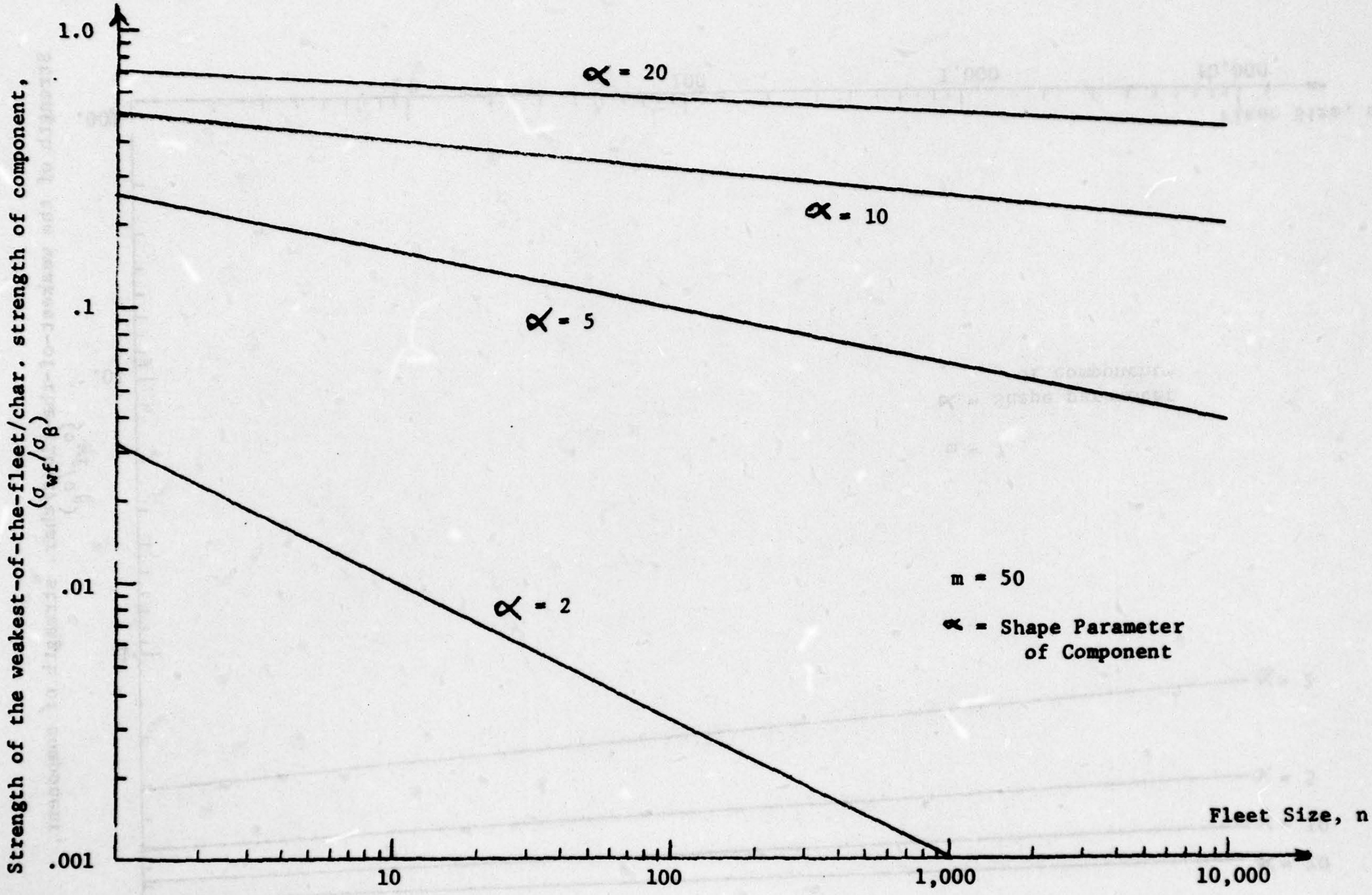


Figure 8. Strength of the Weakest-of-the-Fleet, of n Aircraft. Each Aircraft with 50 Basic in-series Components; Failure of Any is Fatal to the Aircraft. Reliability of 95%.

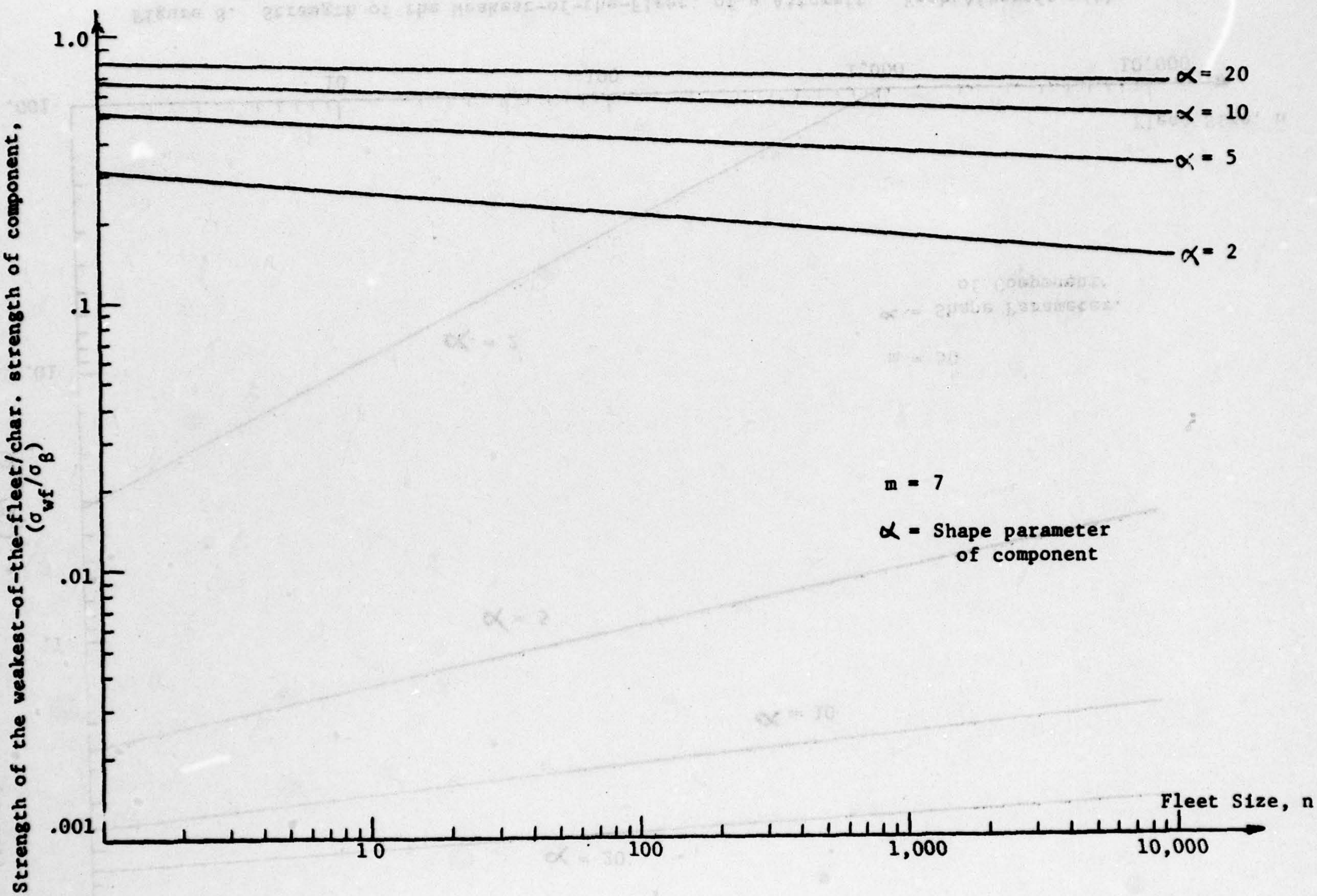


Figure 9. Strength of the Weakest-of-the-Fleet, of n Aircraft. Each Aircraft with 7 Basic in-parallel Components; after One Fails, Surviving Components Share Load Equally. Reliability of 95%.

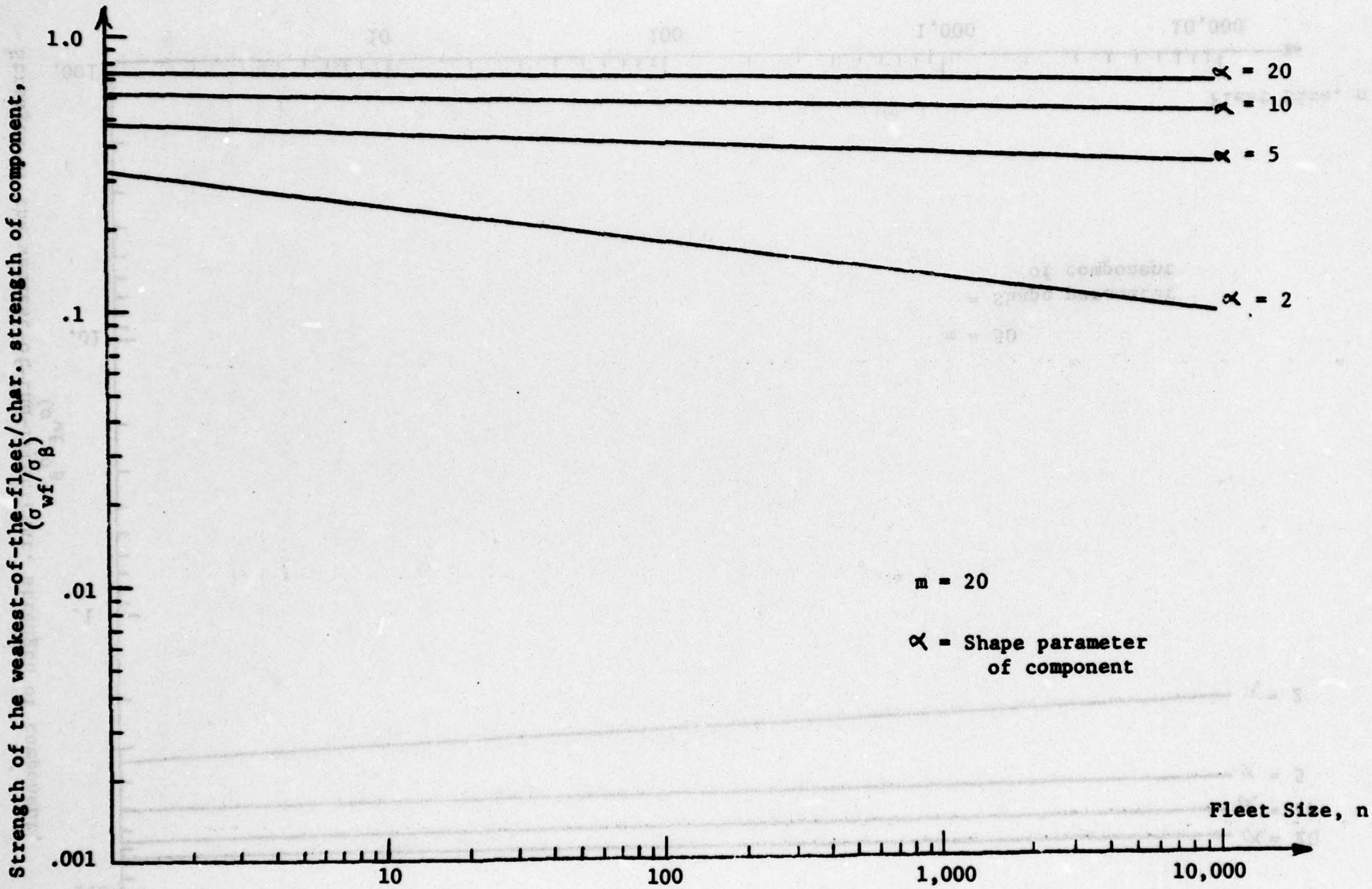


Figure 10. Strength of the Weakest-of-the-Fleet, of n Aircraft. Each Aircraft with 20 Basic in-parallel Components; after One Fails, Surviving Components Share Load Equally. Reliability of 95%.

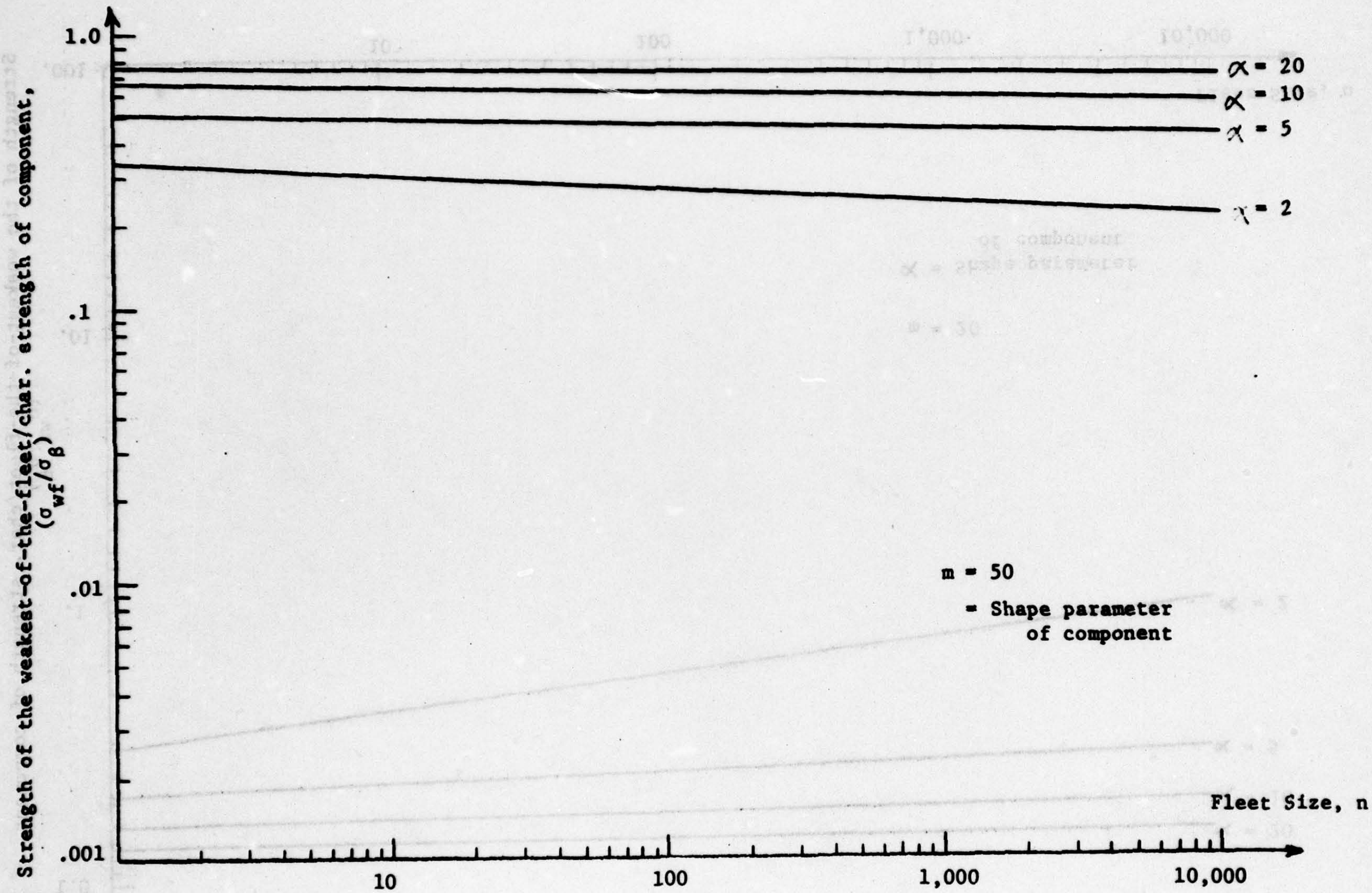


Figure 11. Strength of the Weakest-of-the-Fleet, of n Aircraft. Each Aircraft with 50 Basic in-parallel Components; after One Fails, Surviving Components Share Load Equally. Reliability of 95%.

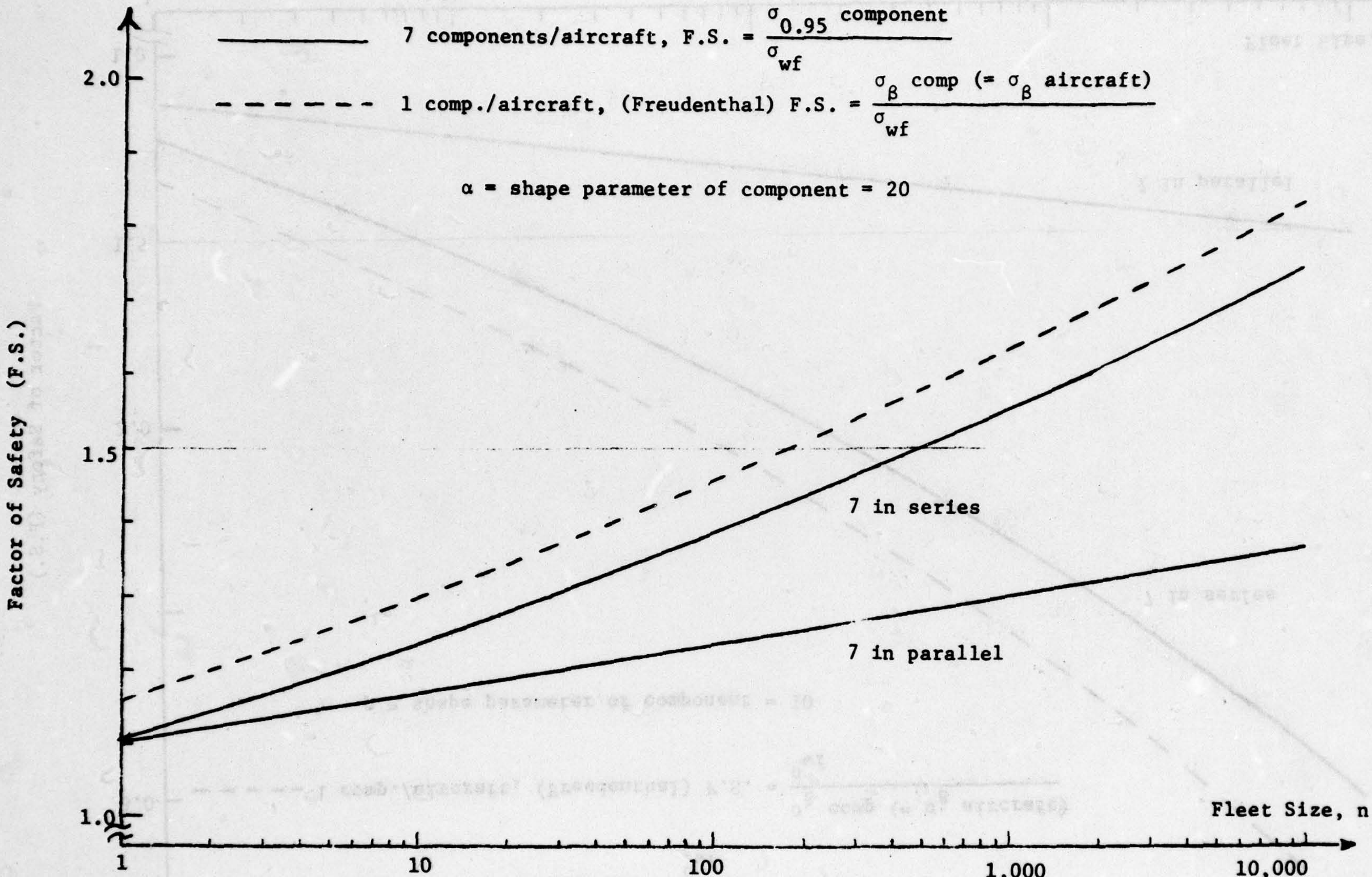


Figure 12. Factor of Safety Required for No Failure of Any Aircraft in the Fleet with 95% Reliability. Typical Metal Structure

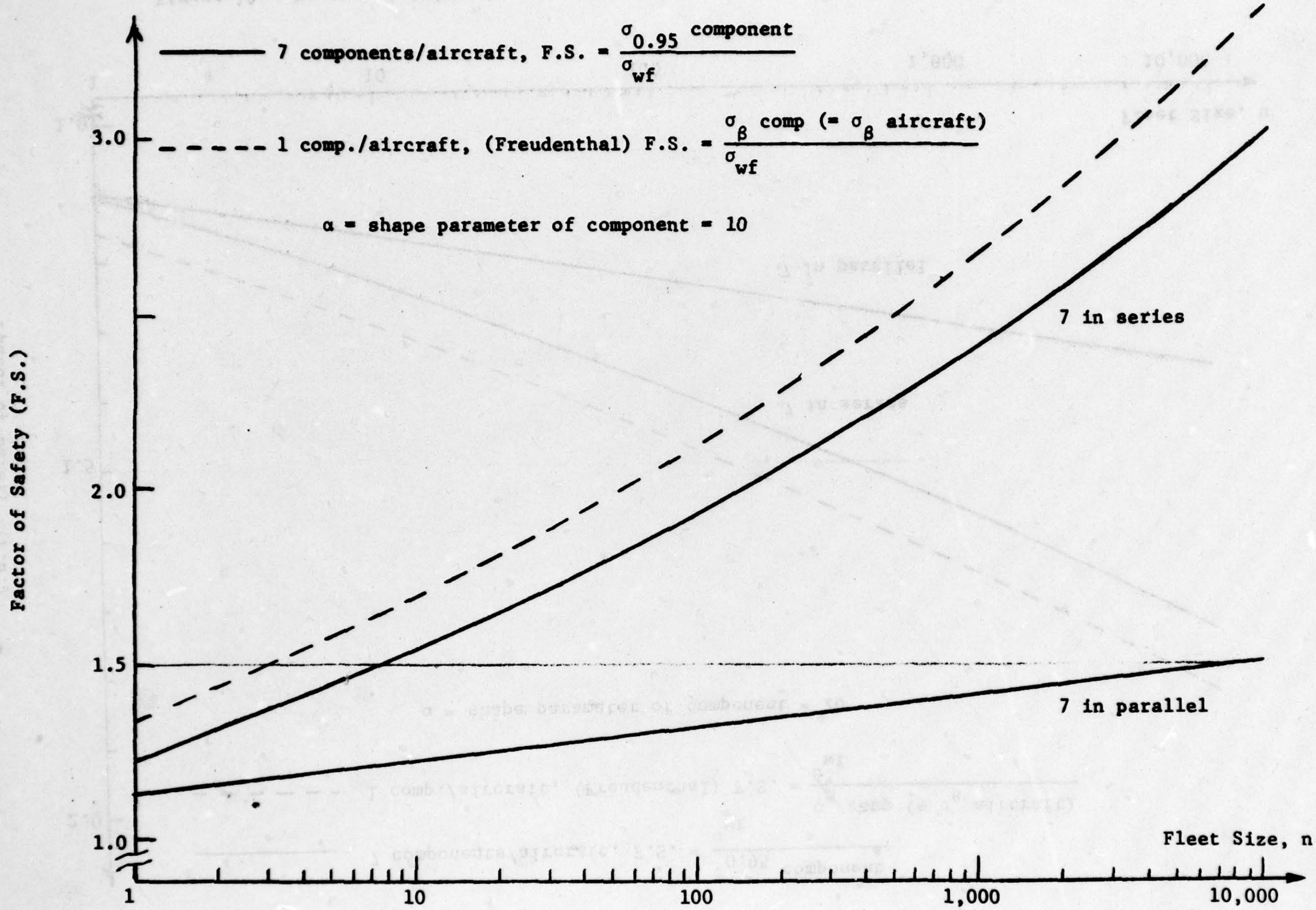


Figure 13. Factor of Safety Required for No Failure of Any Aircraft in the Fleet with 95% Reliability. Typical Composite Structure.

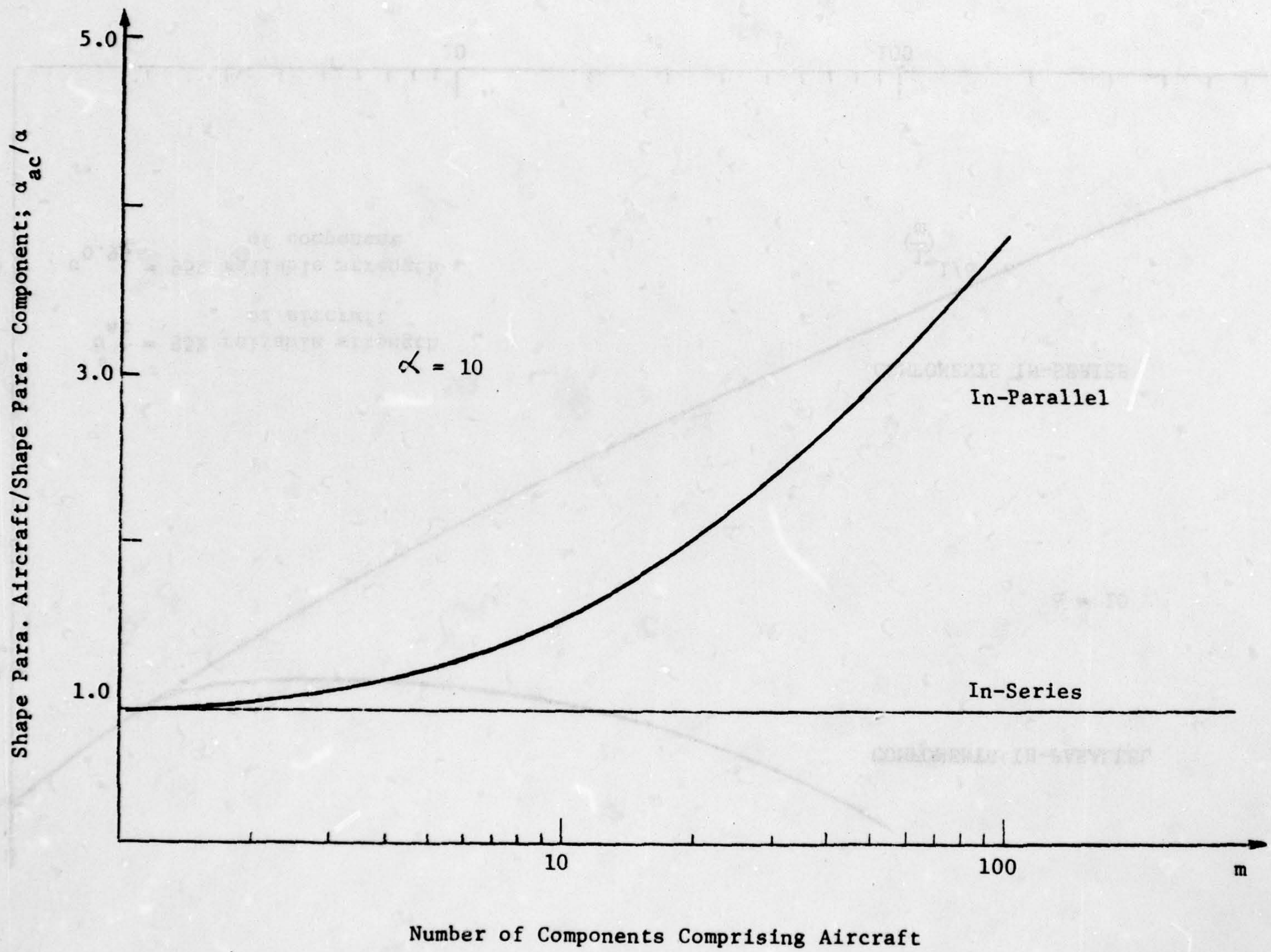


Figure 14. Shape Parameter of the Aircraft versus Number of Components Curves.

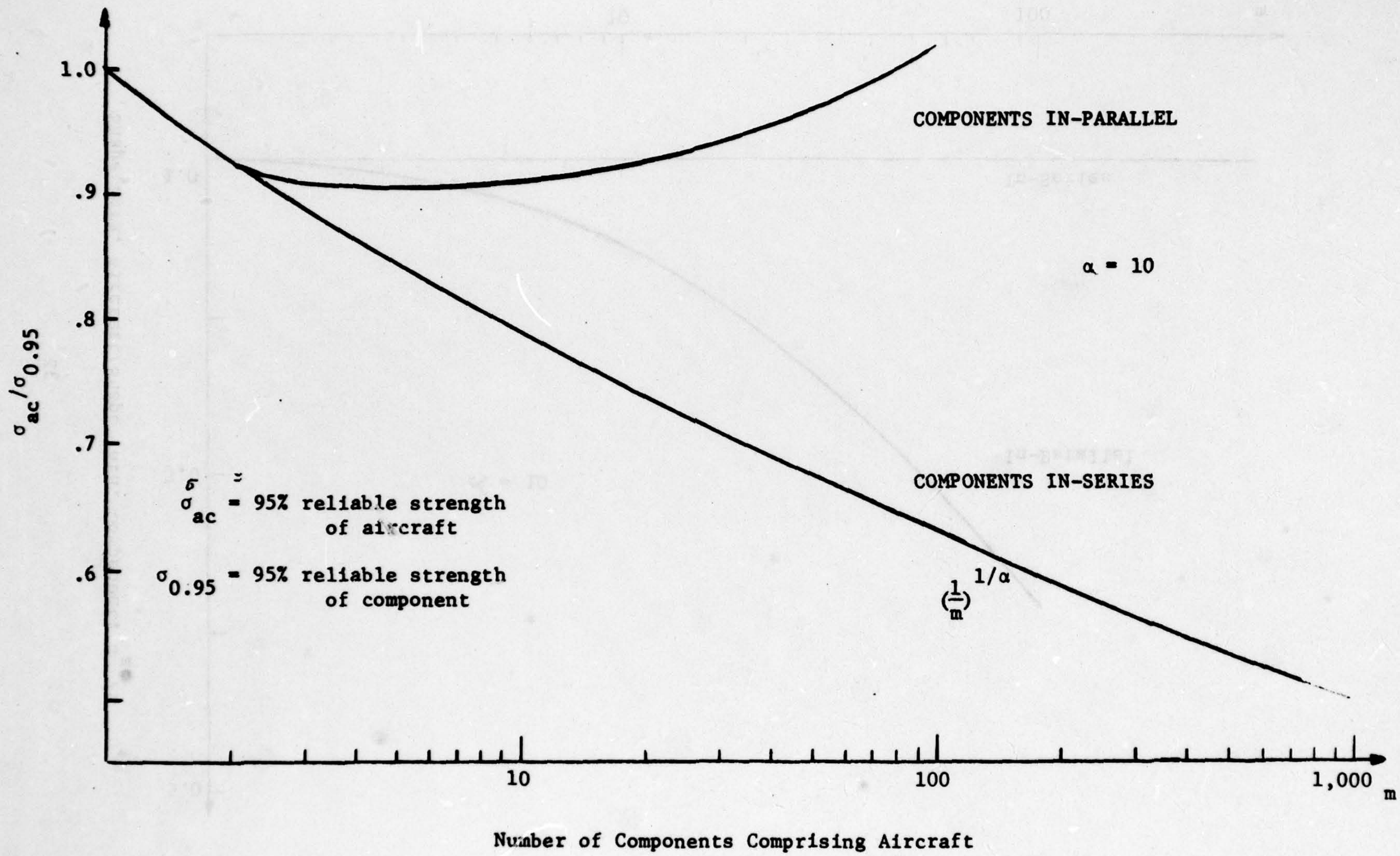


Figure 15. The 95% Reliable Strength of the Aircraft versus the Number of Components, for both Parallel and Series Arrangements.

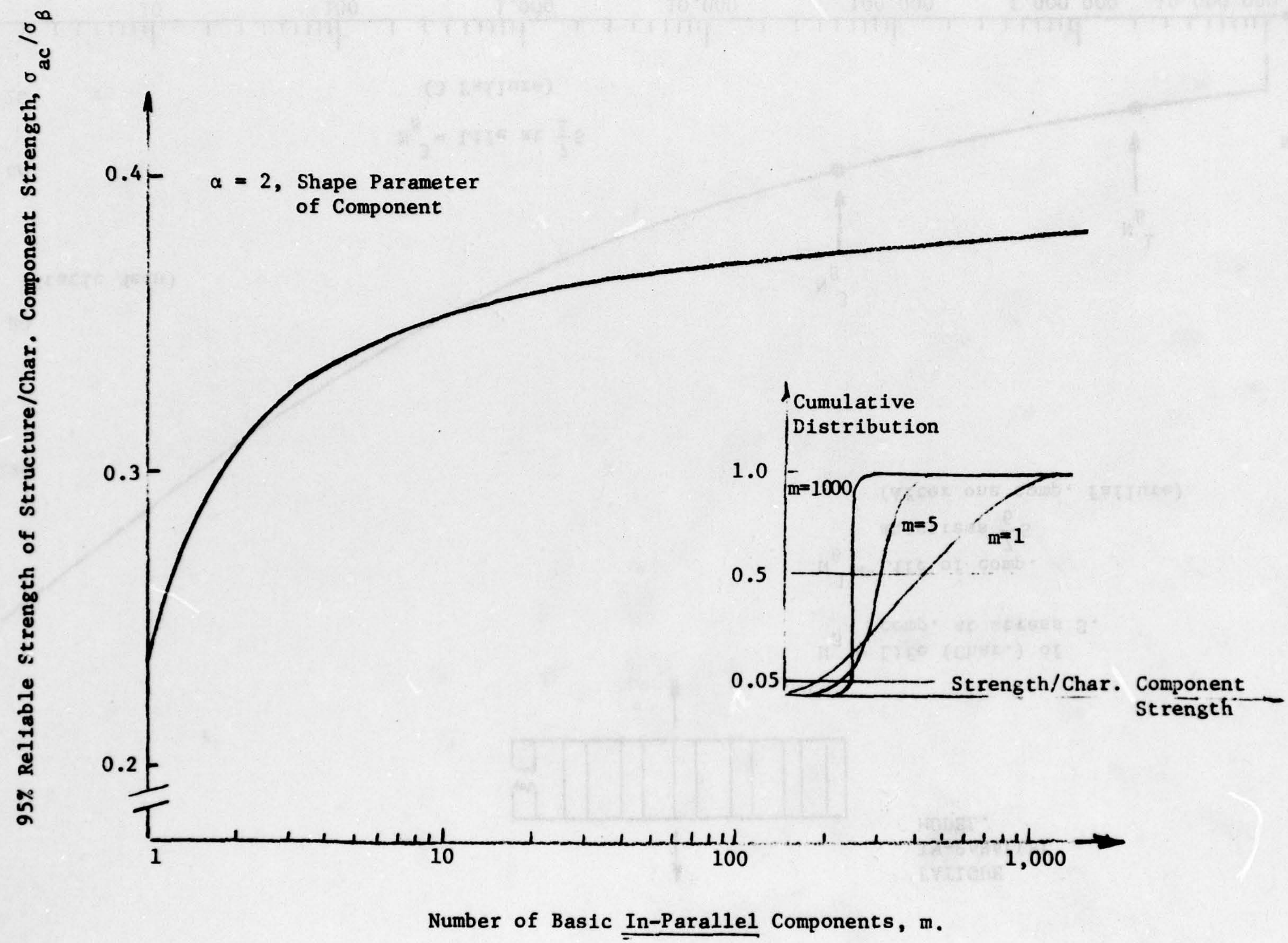


Figure 16. The 95% Reliable Strength of an In-Parallel Structure versus the Number of Components

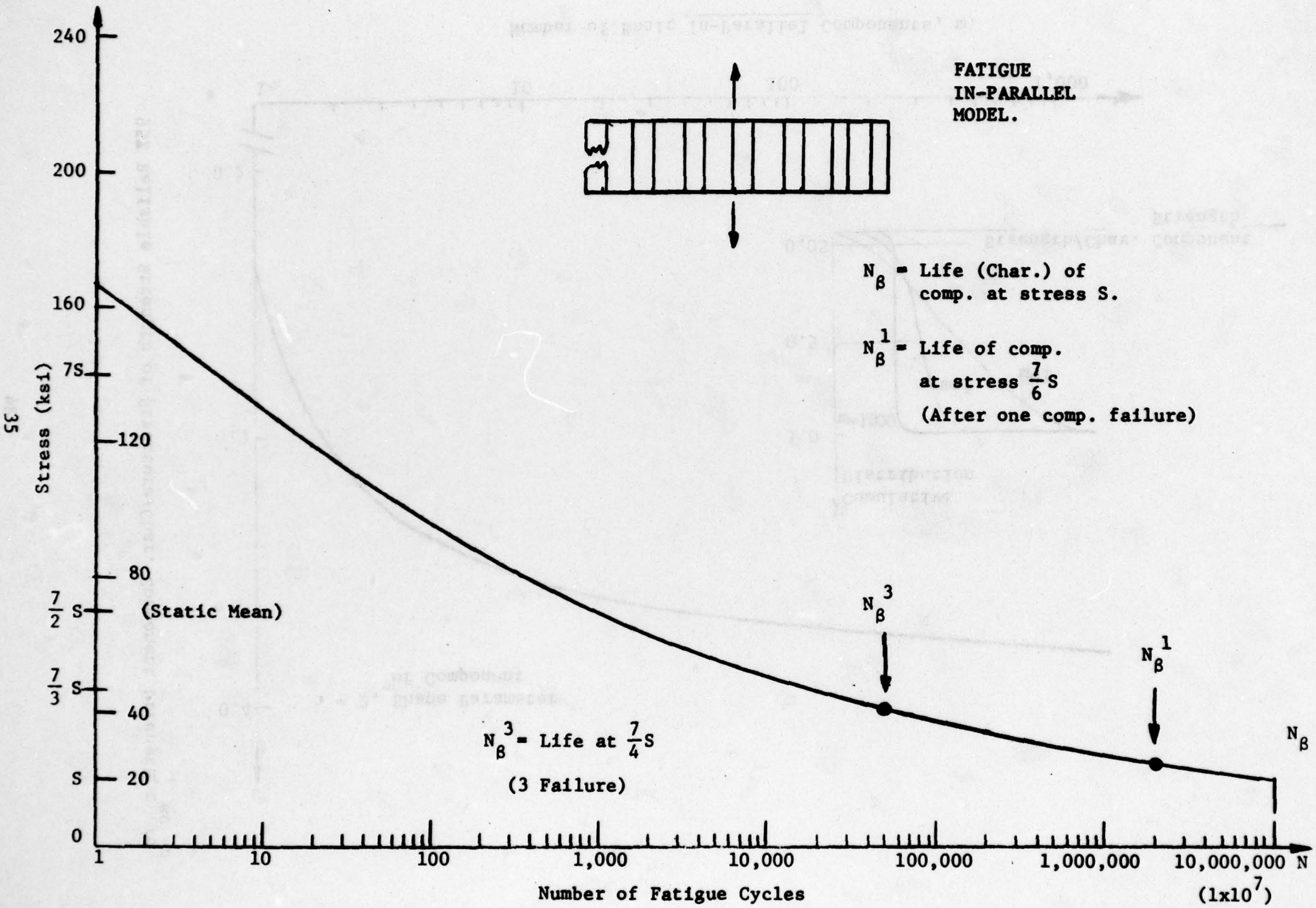


Figure 17. SN Curve for Fatigue of 7 Components in Parallel

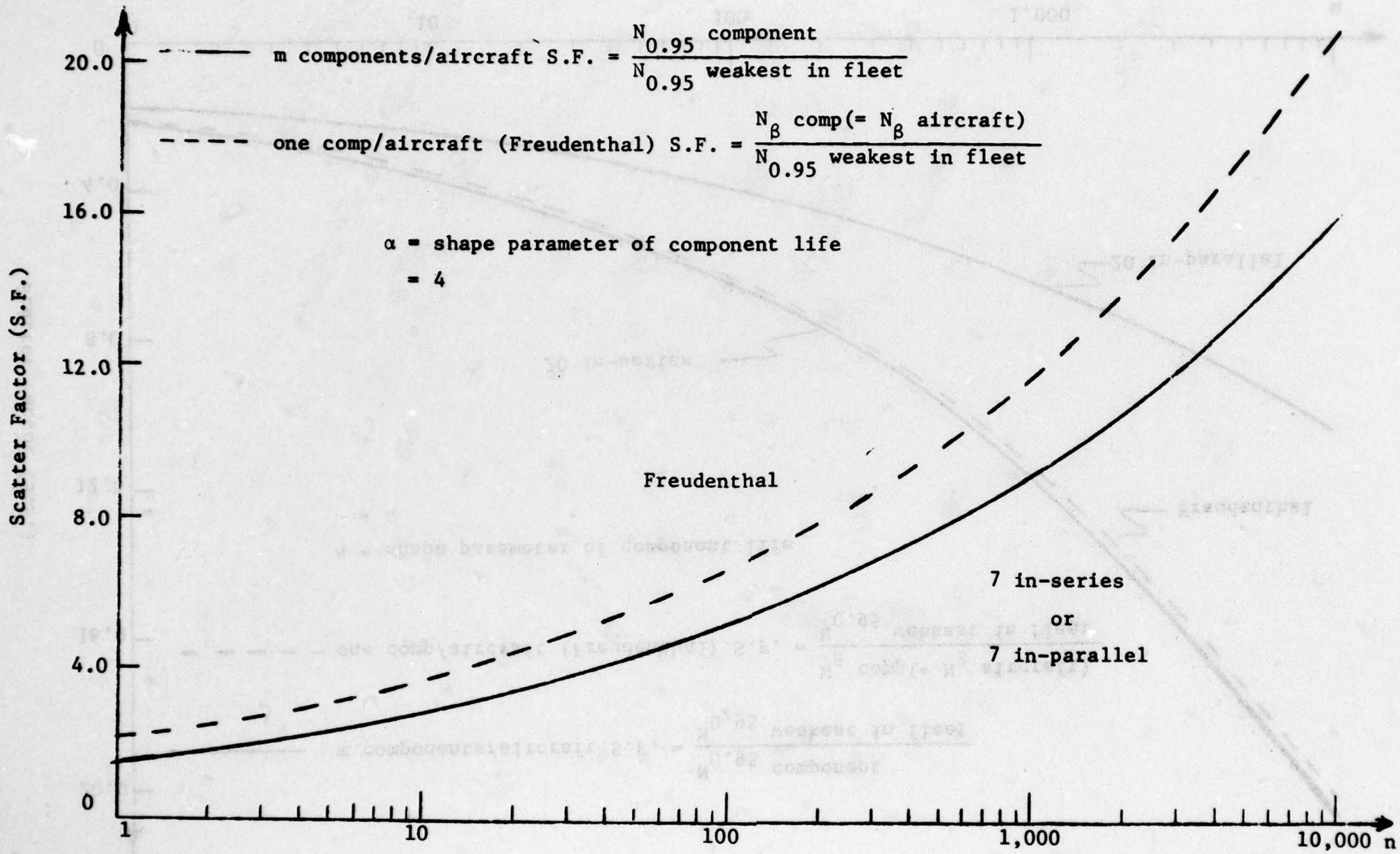


Figure 18. Scatter Factor Required for No Fatigue Failure of Any Aircraft in the Fleet, with 95% Reliability. Typical Metal Structure with Seven Components

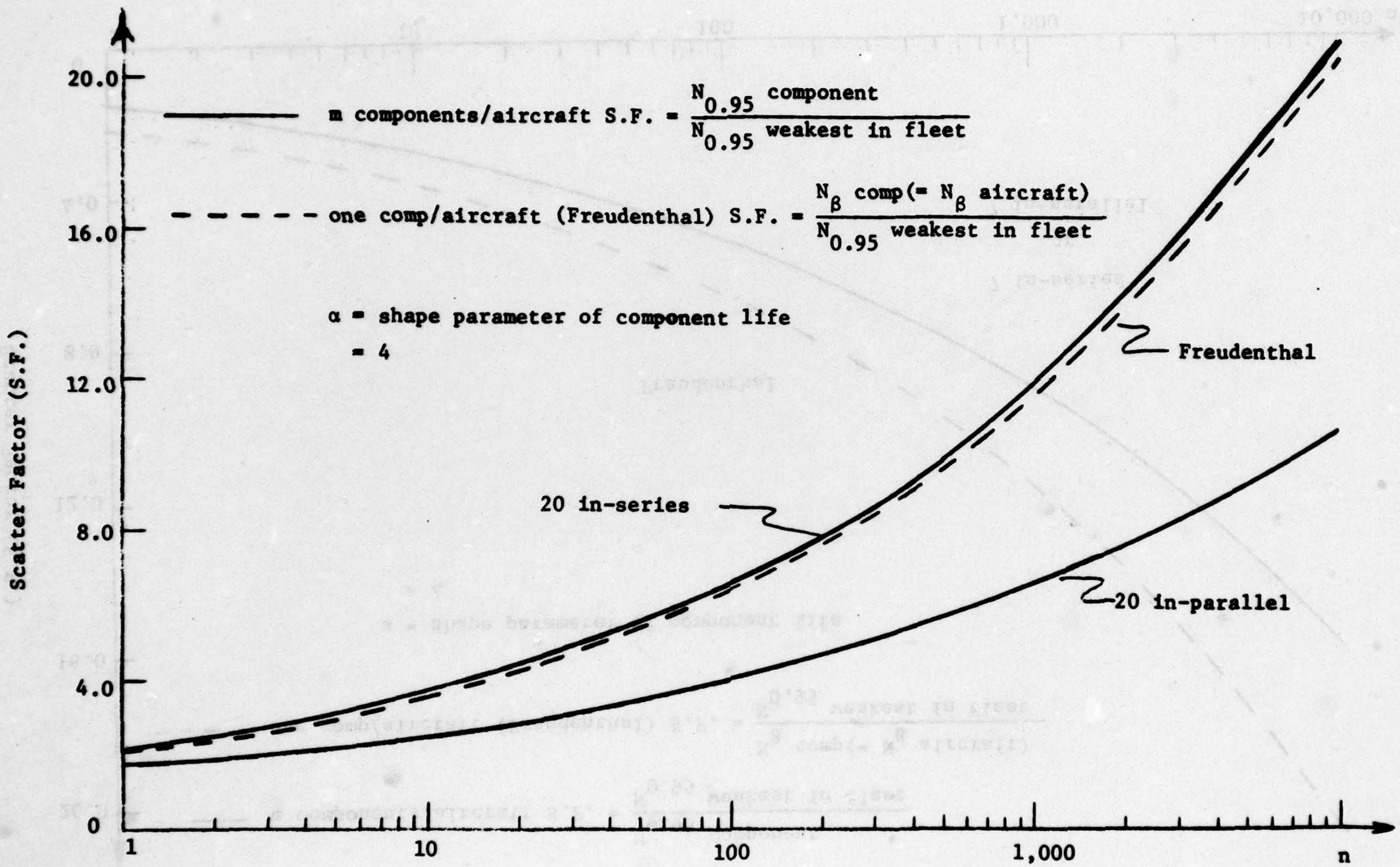


Figure 19. Scatter Factor Required for No Fatigue Failure of Any Aircraft in the Fleet, with 95% Reliability. Typical Metal Structure with 20 Components

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